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NSWC/DL TECHNICAL REPORT TR-3313
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FOREWORD

The experimental test reported was requested by the Office of the Army Material Command Program Manager for the Demilitarization of Chemical Material. The work was performed from December 1974 through March 1975 by the Electro-Optics Branch, Guidance and Control Division, Advanced Systems Department.

This report was reviewed for technical content and approved by: L. J. Fontenot, Head, Electro-Optics Branch, Guidance and Control Division and R. L. Schmidt, Head, Guidance and Control Division.

Released by:

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ABSTRACT

Experimental results of using a forward looking infrared (FLIR) thermal imaging system to monitor the spray dryer stack effluent at Rocky Mountain Arsenal, Colorado, are presented. The effluent was emitted in the demilitarization process of GB nerve gas.

Since the effluent was mostly water vapor with very small quantities of residue GB, a strong infrared absorber that approximated the molecular weight of GB, sulfur hexafluoride (SF_6), was added to the stack to aid tracking. Without the SF_6, the plume extent was seen as readily by visual means as with a FLIR. With SF_6 added to the stack, the plume was tracked from ranges of hundreds of yards to several miles, depending upon the meteorological and background conditions. Finally, two FLIR units, in conjunction with a mobile air sampler unit of the Army Environmental Hygiene Agency, used triangulation to successfully locate the area where the spray dryer plume reached ground level under several meteorological conditions.

Furthermore, it was concluded that a thermal imaging device, coupled with a high spectral resolution spectrometer, would be useful in detecting air pollution during day or night operations.

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INTRODUCTION

BACKGROUND

One major task of the Office of the Army Material Command Program Manager for Demilitarization of Chemical Materials is to neutralize the lethal nerve gas GB presently contained in M34 bombs and ton containers at Rocky Mountain Arsenal (RMA), Colorado. The technique used is to mix the GB liquid with a caustic material, then dry the brine solution for easy storage. Unfortunately, all the GB is not neutralized in the process and a residue amount is released as part of the spray dryer effluent. The maximum ground level exposure dosage of GB allowed by the Department of Health, Education, and Welfare for any 24-hr period is 5×10^{-3} mg-min/m^3 (2×10^{-4} mg/m^3 averaged over a 1-hr period, 3×10^{-6} mg/m^3 averaged over a 24-hr period, or any product of time and agent concentration which is equal to 5×10^{-3} mg-min/m^3). To determine those conditions under which the spray dryer could be operated in conjunction with other GB emission sources within the maximum ground level exposure dosage, the Army Environmental Hygiene Agency (USAEHA) was tasked to directly measure by air sampling techniques the plume effluent at the spray dryer stack and at the ground position of maximum concentration. This ground position was determined as follows:

1. The approximate position was calculated using a dispersion model with the current meteorological conditions.

2. The correct position was confirmed by the detection of sulfur which was added to the spray dryer stack to aid tracking. Sulfur hexafluoride (SF_6) was used as the stack additive because it approximates the molecular weight of GB.

The results of USAEHA testing at RMA in October and November 1974, indicated that with brine resulting from the neutralization of GB with tributylamine (TBA), a 6-gpm brine input rate to the spray dryer, and gas or fuel oil firing of the spray dryer:

1. The spray dryer, because of its shorter stack and greater agent emission rate, is the predominant source for measurable ground level agent concentrations.

2. The average agent emission concentration with brine resulting from the neutralization of TBA stabilized agent and a 6-gpm brine input rate was 8.4×10^{-4} mg/m^3 with natural gas firing and 61.0×10^{-4} mg/m^3 with fuel oil firing.

3. Ground level agent concentration exceeding 3×10^{-6} mg/m^3 can be expected when the agent emission concentration from the spray dryer surpasses 3×10^{-4} mg/m^3 during A, B, or C stability (Table 1).

4. Ground level agent concentrations exceeding 3×10^{-6} mg/m^3 can be expected when the agent emission concentration from the spray dryer surpasses 3×10^{-4} mg/m^3 during D stability and surface wind speeds greater than 10 mph.

Table 1. Meteorological Stability Categories

Average Surface Wind Speed (mph)	Day: Solar Radiation			Night	
	Strong	Moderate	Slight	Thin Overcast or >4/8 Low Cloud Cover	Thin Overcast or >3/8 Cloud Cover
<4	A	A-B	B	F	F
4-7	A-B	B	C	E	F
7-11	B	B-C	C	D	E
11-13	C	C-D	D	D	D
>13	C	D	D	D	D

SCOPE AND OBJECTIVES

The Naval Surface Weapons Center/Dahlgren Laboratory (NSWC/DL) was requested by the Demilitarization of Chemical Materials Office to monitor the spray dryer stack effluent with a high resolution thermal imaging sensor--forward looking infrared (FLIR). The objectives were to:

1. Determine the spray dryer plume dispersion configuration during low wind speed, stable meteorological conditions.

2. Determine the spray dryer plume dispersion configuration when subjected to aerodynamic downwash.

3. Determine if two FLIR units, with and without the use of an SF_6 tracer, can be used to locate the area where the spray dryer plume reaches ground level.

4. Continued the evaluation of ground level agent concentration during E and F stability and low wind speed D stability.

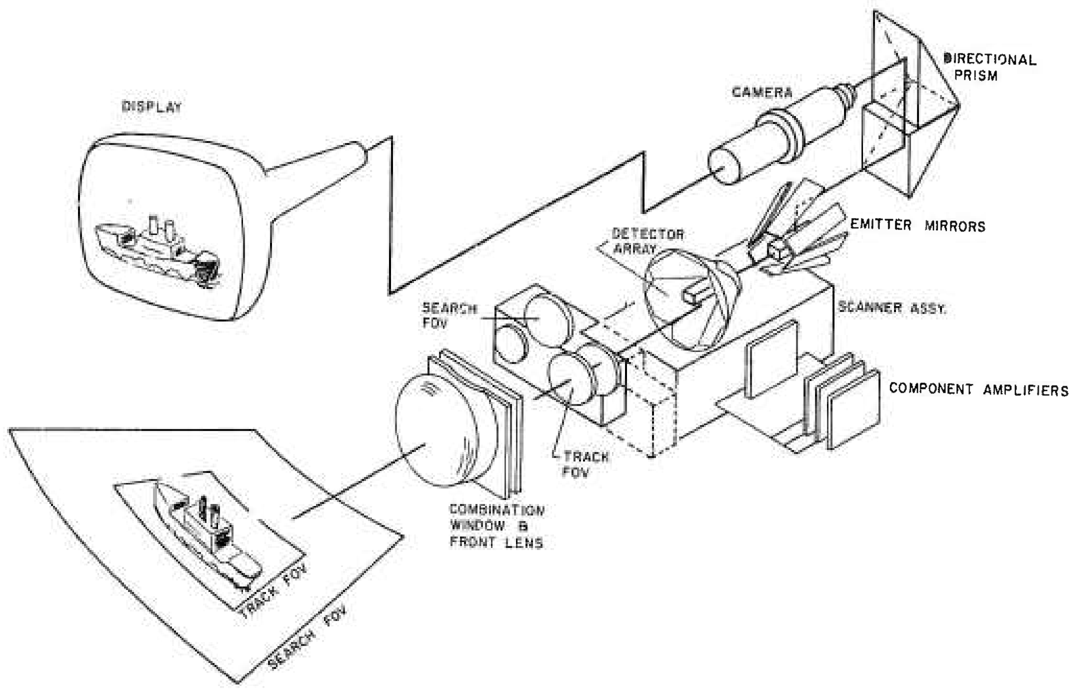
5. Evaluate the effect of removing the "diffuser cap" from the spray dryer stack on ground level agent concentration.

TEST EQUIPMENT

The FLIR set is a system which provides a visual presentation of target objects within its field of view (FOV) and is passive in that it senses an object by detecting the infrared energy radiated by the object. Since the FLIR responds to the self-emitted radiation of an object, it is effective in both day and night operations. Infrared reception is affected by the amount of energy lost due to atmospheric absorption, scattering, and particles in the atmosphere. FLIR utilizes optical means to focus the infrared energy onto detectors which convert the infrared energy into electrical energy. The electrical signals are amplified and processed by electronic circuitry within the infrared receiver for viewing on a cathode ray tube (CRT).

The FLIR used in the test was a Texas Instruments Model AN/AAS-28A (Figure 1). In operation, infrared radiation from a target is collected by the front lens and is focused onto infrared detectors by either of two optical systems (search or track). The search optics provide a wide FOV, while the track optics provide a narrow FOV. Incoming radiation is scanned by a set of six rotating scan mirrors. The optics and scanning mechanism focus the incoming infrared radiation onto the detector linear array. The mercury cadmium telluride detectors use the incoming infrared radiation to modulate an electrical current proportional to the incident radiation. The electrical signal produced by the detectors is amplified by video amplifiers which provide a signal large enough to modulate the light-emitting diodes. The radiation from the gallium-arsenide emitters is reflected through a set of four rotating scan mirrors onto a folding mirror which directs the radiation onto a vidicon target. The vidicon target is then scanned at interlaced 30-frame-per-second television scan rates by a camera gun assembly. The output of the gun assembly is single channel composite video, which is processed and used to modulate a CRT for display.

Two AN/AAS-28A units were used for the testing at RMA. Both units were tripod-mounted (Figure 2) for ease of movement between tests.



Spectral Band: 8 to 13 micrometers (nominal)

Field of View

Search: 7.3 x 9.7°

Track: 1.8 x 2.4°

Detector Type: Mercury cadmium telluride

TV Scan Rate: 30 frames per sec, 2:1 interlace

Scan Format: Wiper blade

Display: 875 TV lines

Cooling: TI compressor cools to 77°K

Figure 1. Schematic and Features of AN/AAS-28A FLIR

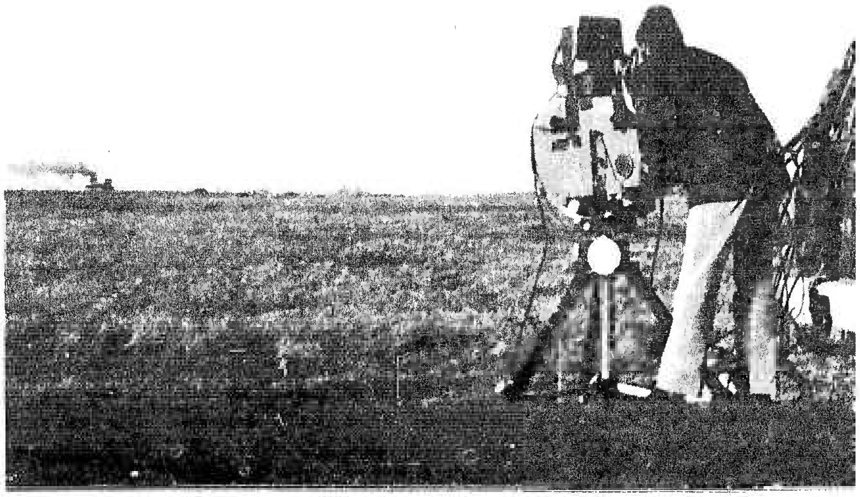


Figure 2. Tripod-Mounted AN/AAS-28A FLIR at RMA

TEST PROCEDURES AND RESULTS

PRELIMINARY TESTS AT NSWC/DL

To determine if the concept of tracking the spray dryer exhaust effluent with FLIR were feasible, a series of quick tests were conducted at NSWC/DL in December 1974. First, a steam generator was placed 100 ft from the FLIR to track the plume. It was found, as expected, that the water vapor plume was tracked with FLIR about as far as the plume was visible to the eye. Second, various quantities of SF_6 were released from a pressurized container and tracked with FLIR. Against a low-angle sky background (the conditions anticipated at RMA), the vaporous SF_6 was detected and tracked with FLIR. The estimated "CL" value detected by FLIR in this exercise was about 80 mg/m^2 [Cl (mg/m^2) = concentration

x depth]. Figure 3* shows FLIR imagery of an SF_6 vapor cloud observed during the tests at NSWC/DL. Table 2 shows the physical parameters of SF_6. The spectral absorption curve of SF_6 in Figure 4 shows that SF_6 is a very strong absorber near 10.6 micrometers.

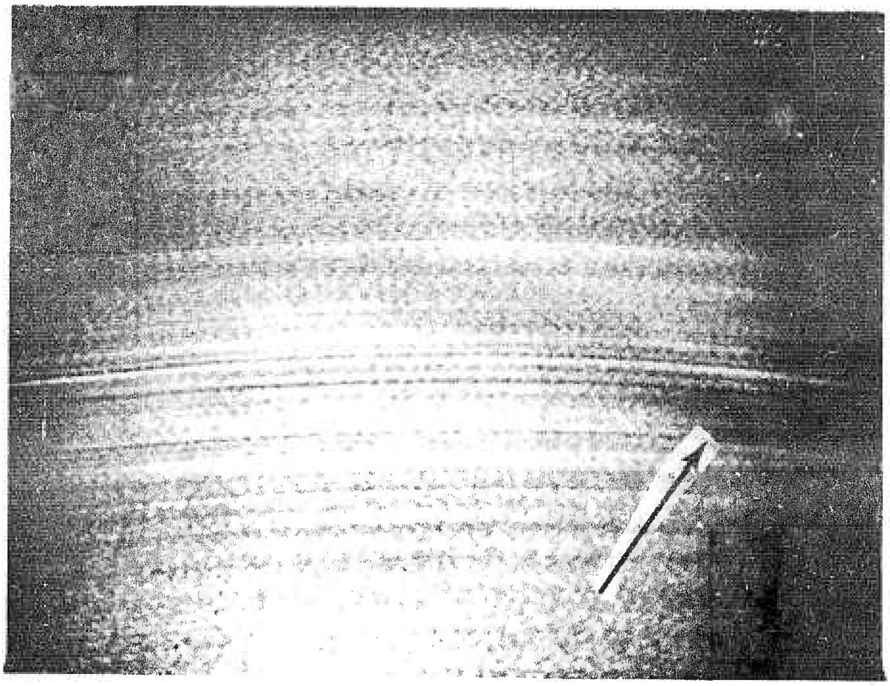


Figure 3. FLIR Imagery of SF_6 Vapor Cloud (Black = Hot)

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* Since a plume dispersion is a dynamic event, the still photographs of the FLIR imagery presented herein do not adequately illustrate the ease of detection and tracking to the observer of the FLIR display. FLIR was always set on black = hot for this program.

Table 2. SF_6 Physical Parameters

Molecular weight	146.054
Density, gas @ 0°C, 1 atm	6.52 g/l
Specific volume @ 70°F, 1 atm	2.5 ft^3/lb (156.1 ml/g)
Vapor pressure @ 70°F, 1 atm	320 psig (22.5 kg/cm^2 gauge)

NOTE: SF_6 has a low order of toxicity. The 1968 American Conference of Governmental Industrial Hygienists recommended a threshold limit value of 1000 ppm for SF_6 (the concentration in air to which nearly all workers may be exposed day after day without adverse effects). SF_6 can, however, act as a simple asphyxiant by displacing the necessary amount of oxygen to support life.

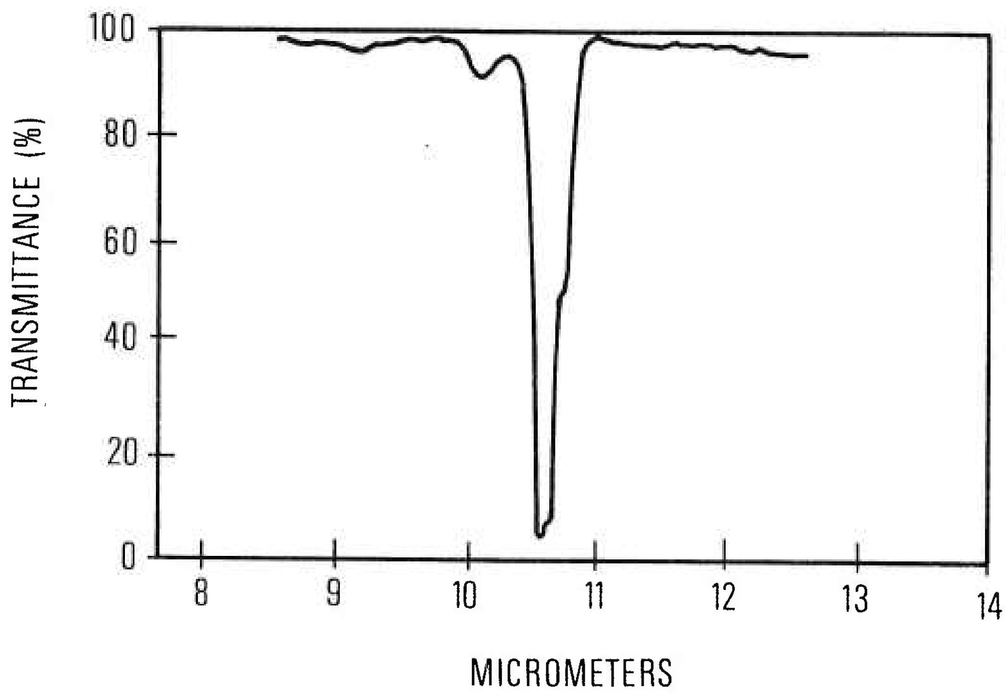


Figure 4. Spectral Absorption Curve of SF_6

Liquid Freon 12 (Cl_2CF_2) which is also a strong absorber in the spectral passband of FLIR was released from micropipettes onto a hot plate. The vaporized CL_2CF_2 was detected by FLIR. The minimum quantity of vaporous CL_2CF_2 that was observed on the FLIR display was about 5 microliters at a range of 100 ft. Figure 5 shows FLIR imagery of this event. The small arrow shows the vaporization of one drop of Freon 12. The dark area designated by the larger arrow is the envelope of the dispersing vapor cloud.

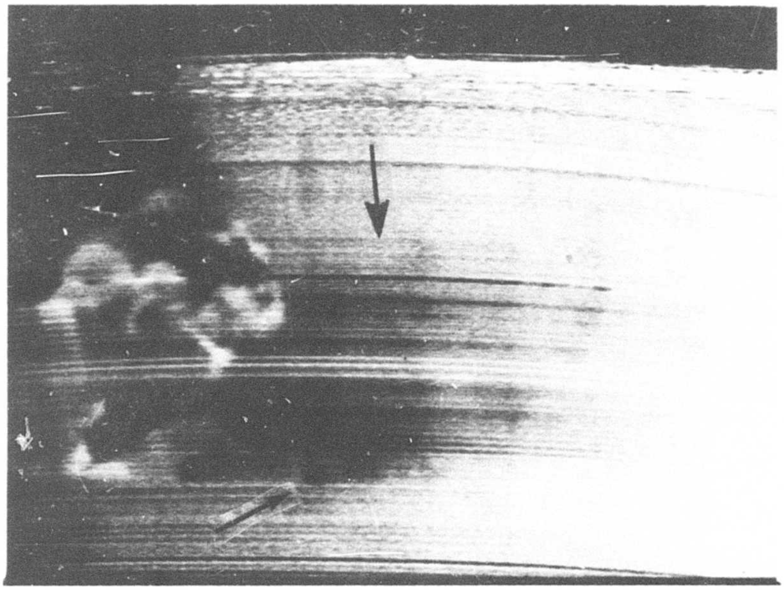


Figure 5. FLIR Imagery of Freon 12 Release

TESTS AT ROCKY MOUNTAIN ARSENAL

TBA-stabilized GB was processed through the existing neutralization facility utilizing sufficient caustic to produce brine with an excess caustic content of 8 percent. The neutralized brine was then transferred to holding tanks. A liquid flow rate of 25 gpm to the sprayer dryer was maintained by supplementing the 6-gpm brine flow with process water. During the tests in January 1975, the spray dryer was fired with natural gas. Figure 6 shows the RMA spray dryer with its exhaust plume that was the object of our monitoring.

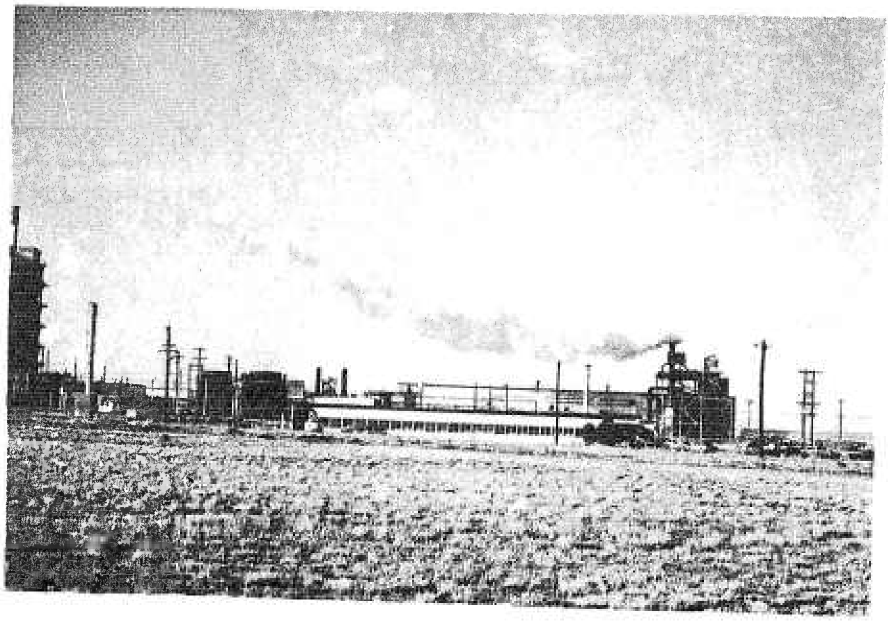


Figure 6. RMA Spray Dryer

The use of FLIR in monitoring was divided into two phases. During phase IA, one FLIR unit was deployed to determine the plume rise and dispersion configuration with normal plume components (1) alone, (2) with SF_6 tracer added at a release rate of approximately 1.7 gm/sec, and (3) with SF_6 at release rates to permit FLIR tracking to the ground. The 1.7-gm/sec flow rate was generated using the USAEHA setup injecting vaporous SF_6 directly from its pressurized container into the spray dryer stack. Figure 7 shows higher flow rate setup. A heater tape was added to the pressurized SF_6 container to provide an ample supply of vaporous SF_6 for a series of short bursts into the stack. The holding tank was necessary to release a large quantity of SF_6 gas in a short burst. The valve settings were calibrated to release SF_6 at rates from 5 to greater than 150 gm/sec. This corresponds to a concentration in the stack from 46 to 1400 parts per million.

In phase IIA, two FLIR units were deployed.

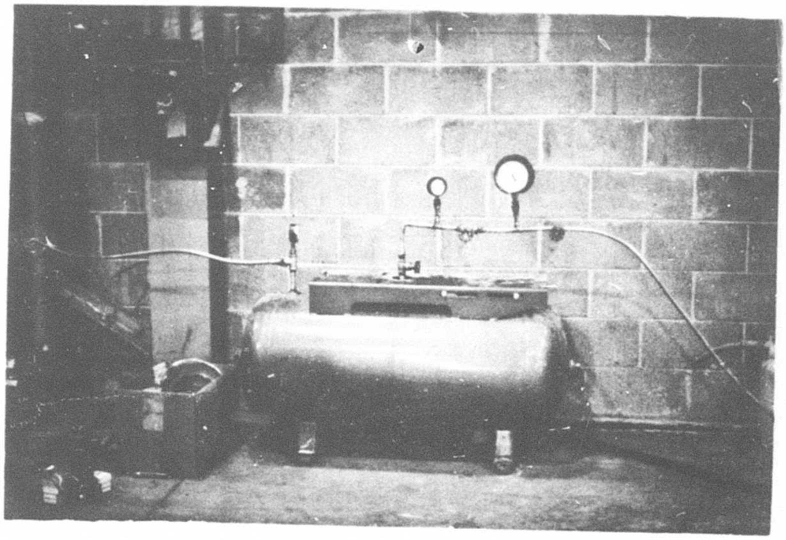


Figure 7. High Flow Rate Set Up

Phase IA Tests

Table 3 presents the results of phase IA tests. The FLIR position during each test was recorded using the grid coordinate system of the M34 area as shown in Figure 8. Table 4 lists the meteorological conditions during phase IA; only the extreme wind directions during the tests are given.

Several observations were made from the phase IA tests:

1. The backgrounds from the FLIR positions during the phase IA tests were not optimum for maximum target-to-background temperature difference. The backgrounds were mostly low clouds (0 to 5 kft) whose apparent temperature in the FLIR spectral band was near ambient. Thus a low temperature difference between the plume and the cloud background resulted in low contrast imagery and short tracking ranges.

2. During the day, the plume with no SF_6 and with the 1.7-gm/sec flow rate had the same extent both visually and as seen on the FLIR display.

Table 3. Plume Characteristics During Phase IA Tests

Date	Time	Site[a]	Characteristics
14 Jan 1975	0930	2.9/2.3	Very little turbulence or mixing occurred. The centroid rise rate was extremely low. Plume base was tracked almost to the ground (~15 ft).
	1900-1930		No turbulence evident. The plume centroid rose slowly, but the base remained low (almost to the ground).
15 Jan 1975	1910-2020	2.6/7th Ave	Substantial instability was noted. Sawtooth type mixing with associated turbulence was common. Portions of the plume approached and/or hit the ground. The average plume rise rate was high, carrying the main body well over Building 1501. This line was modulated by the sawtooth pattern mentioned above. The portions that reached the ground took the form of loops that were "stripped off" the main body and then "slapped" to the ground.
17 Jan 1975	1440-1510	2.7/2.9	There was some downwash, but it was not strong and did not reach the ground. There was some undulation of the plume and it broke up into tuffs which, however, remained well contained in the plume. The main body rose slowly.
	1910-1935		The rise rate, if any, was too low to be observed. The plume undulated, sometimes strongly. No portions reached the ground. Fairly strong vertical mixing was noted, sometimes forming localized nodes in the plume.
21 Jan 1975	2130-2150	2.9/2.3	The plume was quite tight--little spreading. The only evidence of turbulence was a "curd like" appearance. The rise rate was low. The maximum observed centroid height was 100 ft.

[a]See Figure 8.

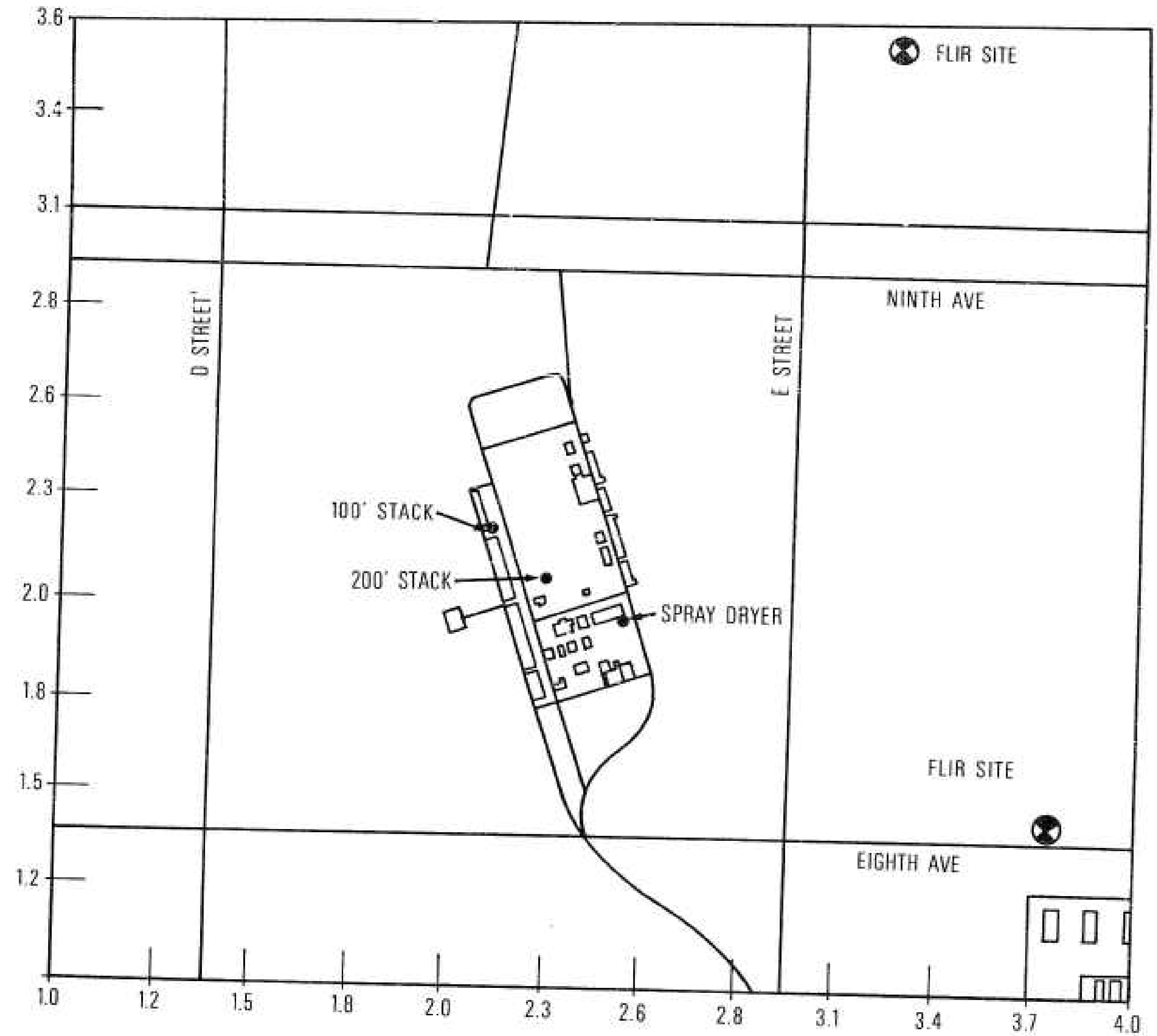


Figure 8. RMA Grid Coordinate System

Table 4. General Weather Conditions During Phase IA Tests

Date	Time	Temperature (°F)	RH (%)	Visibility (miles)	Cloud Cover (1/10ths)	Cloud Type*	Height (ft)	Wind Speed (mph)	Wind Direction
10 Jan 1975	1900-2000	22	32	20	9-10	8 As	12,000	0-3	Variable
14 Jan 1975	0840-0930	53-55	16	65	9	0 Sc	6,500	3-12	Variable
	1900-1930	53-51	18	20	8	2 Ac	1,400	13-16	270
15 Jan 1975	1900-2030	34	64	20	10	8 S	2,400	7	80
17 Jan 1975	1430-1510	55	23	60	10	0 Sc	6,000		260
	1900-1930	52	30	20	9	2 Ac	13,000		260
21 Jan 1975	2125-2150	11	80	20	0	--	--		180
22 Jan 1975	2115-2230	24	75	20	1	3 Ac	10,000	10	Variable

NOTE: As an example of how to read cloud type, in line one 8 As means 8/10 of altostratus clouds are at an altitude of 12,000 ft.

*Ac = altocumulus
As = altostratus
C = cirrus
Cs = cirrostratus
K = smoke
S = stratus
Sc = stratocumulus

3. An SF_6 flow rate of greater than 50 gm/sec was required to track the plume during both day and night tests. The test on 14 January 1975 demonstrated that the FLIR could track the plume sufficiently well to predict the ground area of greatest concentration.

4. The plume plus SF_6 additive could be tracked better during the night than during the day. This is due to the greater apparent temperature difference ($\Delta T'$) between the plume and background. Also, a clear sky background at night provided the greatest $\Delta T'$. It is interesting to note that what appeared to be a clear night sky to the human observer in a few tests and recorded as such at the Denver Stapleton Airport was observed by FLIR to contain high clouds ($\sim$20 kft) and a nonuniform background (Figure 9).

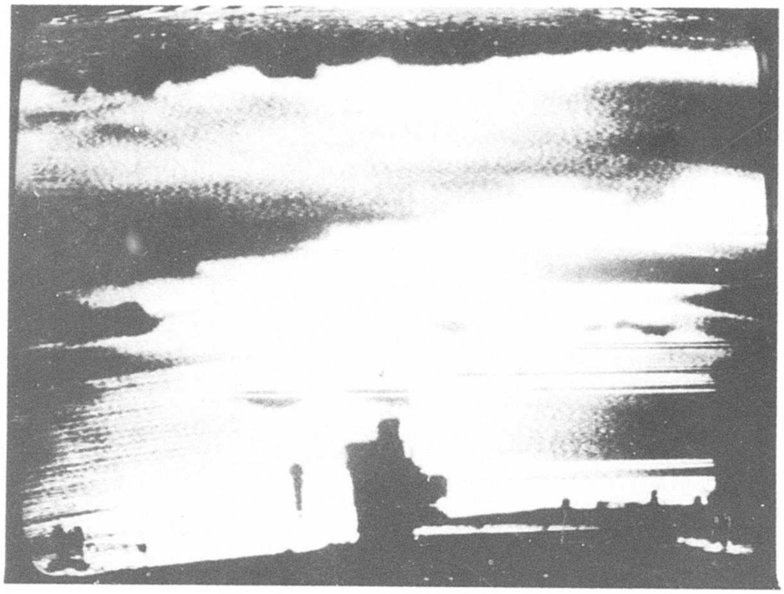


Figure 9. FLIR Imagery of Nonuniform Cloud/Sky Background

Phase IIA Tests

In phase IIA tests, two FLIR units were deployed. Triangulation was used to estimate the location of plume maximum concentration on the ground. The location of the FLIR units for each test was recorded using the grid coordinate system in Figure 8. The grid point of plume touchdown depicted by FLIR was recorded and used to either direct to or verify the mobile sampler positions. When the mobile sampler had located the plume and initiated air sampling, the FLIR was used to verify whether or not the plume shifted during the 30-min sampling period. Table 5 presents the results of phase IIA tests and Table 6 describes the plume characteristics. Table 7 lists the meteorological conditions.

Table 5. Results of Phase IIA Testing

Date	Test No.	FLIR Locations	Plume Maximum Concentration Position: FLIR	Dispersion Model	Mobile Sampler
22 Jan 1975	4D-3-3 (2030-2230)	3.7/1.5 2.9/3.7	2.3/2.9	2.3/3.3	2.3/2.9
23 Jan 1975	4D-1-3 (1330-2030)	3.7/1.5 2.9/3.7	3.7/2.3	3.7/2.8	3.9/2.8
24 Jan 1975	4D-4-3 (1630-1330)	3.7/1.5 2.9/3.7	3.7/2.3	3.7/1.6	3.7/1.4 3.7/2.1
28 Jan 1975	(1830-2030)	3.7/1.4 2.9/3.7	2.8/1.9	2.8/1.9	2.8/1.9
29 Jan 1975	4D-5-3A (1830-2030)	3.7/1.4 2.9/3.7	3.7/0.5	2.7/1.0	3.3/1.0
30 Jan 1975	4E-2-3 (1630-1830)	2.6/7th Ave 3.7/1.4	2.0/1.9	1.9/2.0	2.0/1.9
31 Jan 1975	4E-3-3 (1830-2030)	3.7/1.4 2.9/3.7	2.0/2.2	1.5/2.2	2.0/2.1

Table 6. Plume Characteristics of Phase IIA Tests

Date	Time	Site [a]	Characteristics
22 Jan 1975	2130-2225	2.9/3.7	Poor imagery. No data reduction.
	2130-2225	3.7/1.5	At 2130, the plume rise rate was nearly 60°. There were only minor plume undulations and little plume spread. By 2150, plume rise time reduced to 45° initially but rapidly leveled out such that the centroid did not exceed 100 ft over the ground. Undulations were reduced and nodes became more prominent. By 2208, the initial rise rate was reduced to 30° with the centroid never exceeding 100 ft. By 2225, the undulations were almost gone while the nodal pattern became quite pronounced.
23 Jan 1975	1847-1950	2.9/3.7	Perhaps the best example of the effect of atmospheric instability on plume characteristics. Winds during this period shifted slowly by only 30°. The major factor was the very thin cloud cover which allowed radiational cooling to reduce the temperature from 48°F to 35°F in 1 hr. At 1847, the plume was quite low. The base was about 40 ft over the road when it crossed E St. Very slight modulation of the plume was observed. By 1914, the plume remained over the road crossing (~ 50 ft) but now was vertically sinusoidally modulated. The vertical amplitude at the E St crossing was ~ 250 ft and the wavelength was ~400 ft. By 1950, the plume was severely modulated. Its form was that of a sawtooth. The base was less than 40 ft over E St and the top portion reached 300 ft. The wavelength remained 400 ft.
	1847-2004	3.7/1.5	Centroid rise rate was low all evening (<5°). Height over E St was ~50 ft. At 1847 the form was homogenous. At 1914 there were some nodes evident. By 1953, the plume was rapidly broken up by winds. By 2004, the nodes became the predominant feature.

[a] See Figure 8.

Table 6. Plume Characteristics of Phase IIA Tests (Continued)

24 Date	Time	Site	Characteristics
24 Jan 1975	1640-1725	2.9/3.7	At 1640 the base remained at the initial altitude of the release ($\sim$70 ft). Near the road crossing the plume was nearly 200 ft in vertical extent. The rate of dispersion increased throughout the night. After 1705 there was no obvious increase in instability. The highest concentration at the road crossing was 250 ft up.
	1630-1705	3.7/1.5	Imagery was poor. The plume appeared to come directly at the observer. Cross section was uniform. When the plume crossed E St at vertical grid point 2.2, the base was just above the trees. By 1650, the plume showed no evidence of mixing or turbulence. By 1705, some undulations and mixing were evident The dispersion rate had increased. Centroid height near the stack was about 200 ft and at the E St crossing was 250 ft. Vertical extension was near 250 to 300 ft.
28 Jan 1975	1850-1950	2.9/3.7	Heavy downwash occurred at night. High winds produced substantial mixing in all directions, but the average plume path was actually dropping. It usually hit the ground at the mobile sampler side or near the stack. The plume was broken into random tuffs following random paths. Some were spinning rapidly, suggesting vortex effects.
28 Jan 1975	1835-1916	3.7/1.5	Heavy turbulence and downwash due to high winds. The main body was blown to the ground near the stack close to the mobile sampler. The top of the plume was usually below 100 ft. The conditions continued throughout the test.
29 Jan 1975	1912-2050	2.9/3.7	The test began with very little turbulence or mixing evident. By the middle of the period, there was virtually none. The rise rate was low but steady. This resulted in a retention of plume integrity and insured that no part of the plume reached the ground. In the early tests, the plume passed 150 ft over E St

Table 6. Plume Characteristics of Phase IIA Tests (Continued)

Date	Time	Site	Characteristics
29 Jan 1975 (Continued)	1912-2050	2.9/3.7	As the night progressed, this climb rate increased so that the centroid altitude over E St was 200 ft. Near the end of testing, there was a profound wind shift. For a short period, the plume rose straight up (confirmed by the other site). The wind finally shifted at 2050. The initial climb rate was 12°, but it rapidly fell to zero. Therefore, some portions of the plume nearly reached the tops of the trees. The main body was 200 ft up, and the total vertical extent was 300 ft.
		3.7/1.5	The plume was always uniform with no turbulence until the wind shift. The wind still produced the effect noted above. During the transition, the plume separated into two entities for several minutes.
30 Jan 1975	1658-1755	2.6/7th Ave	The plume followed a well-defined path during this test. The path was directly over Building 1501. The turbulence started at a low level and increased steadily throughout the evening. By 1755, some downwash was evident. The initial burst showed the plume to be well defined. The only evidence of turbulence was a random "curd like" appearance. Subsequent bursts showed a decrease in the rise rate. The base of the plume struck about two-thirds of the way up Building 1501. This trend toward a low rise rate continued throughout the evening.
		3.7/1.5	No turbulence was evident from this aspect. Some of the plume was dispersed by impact with Building 1501. Other than this, the plume climbed steadily and maintained a tight form. The final burst showed a wind shift toward the southwest and some turbulence and mixing.

Table 6. Plume Characteristics of Phase IIA Tests (Continued)

Date	Time	Site	Characteristics
31 Jan 1975	1755-1910	3.7/1.5	During this test some turbulence was noted in the DEMIL area but little outside this region. This produced a tuffed appearance, but the sky background allowed tracking for miles. The plume centroid at 1755 was ~150 ft high and the plume base was ~80 ft up. This increased by 1830 to a centroid height of 180 ft at Building 1501. By 1910, the turbulence had increased causing the plume to subtend a large angular extent. The base was ~120 ft above ground by the time it reached Building 1501.
		2.9/3.7	Same as above. Wind direction and touchdown point were easily determined.

Table 7. General Weather Conditions During Phase IIA Tests

Date	Time	Temperature (°F)	RH (%)	Visibility (miles)	Cloud Cover (1/10ths)	Cloud Type*	Height (ft)	Wind Speed (mph)	Wind Direction
23 Jan 1975	1900–2000	48–35	34–61	20	10	0 Sc	6,000	7–12	250
						0 Ac	12,000		
						0 Ci	25,000		
24 Jan 1975	1600–1700	42	48	25	0	1 Sc	3,000	7–12	270
						0 Sc	7,000		
						8 Ac	11,000		
	1700–1800					1 Ci	25,000	7–12	250
28 Jan 1975	1800–1900	35–31	40	20	0	0 Sc	3,000	18–8	270
29 Jan 1975	1900–2000	31–26	51–57	40–20	10	0 K–	SFC	3–7	110
	2000–2100					10 Cs	25,000	3–7	135
30 Jan 1975	1700–1800	26–24	42–48	15	3	0 Sc	7,000	7–12	45
						3 Ci	25,000		
31 Jan 1975	1800–1900	31–27	61–69	20	0	0 K–	SFC	3–7	270
						0 Sc	4,000		
						0 Ci	25,000		

*Ac = altocumulus
As = altostratus
C = cirrus
Cs = cirrostratus
K = smoke
S = stratus
Sc = stratocumulus

The following observations were derived from the phase IIA tests:

1. The wind shifted significantly during air sampling by the mobile van so that it was nearly impossible to keep the van in the center of the highest effluent concentration area on the ground for its entire sampling period. In some cases, the mobile van would set up in the correct position with the aid of its sulfur detector and/or the FLIR units; however, by the time the van was ready for sampling, the winds shifted the plume direction and/or its characteristics.

2. The FLIR units, by means of triangulation, successfully predicted the ground plume position while the sampler position was either confirmed or successfully redirected to a more correct ground position.

3. The test on 28 January 1975 was conducted during a period when the spray dryer plume was subjected to aerodynamic downwash (D stability and surface winds greater than 10 mph). Figures 10 through 12 show typical FLIR imagery from this condition. The plume was nonuniformly dispersed by the high gusty winds and slammed toward the ground. The FLIR and mobile sampler recorded the same grid position for this test. Figure 10 shows FLIR imagery from grid site 2.9/3.7 of the plume being bent over. (Note the high apparent temperature of the low clouds above the plume--black = hot on the photographs.) Figure 11 is a FLIR image from grid point 3.7/1.4 with the FLIR in its narrow FOV. The figure clearly shows the plume being torn apart by the gusty wind, which is blowing directly toward the FLIR unit. Figure 12 shows the image from site 3.7/1.4 in wide FOV. The plume is bent over, with a small tuft just below the main body of the plume. The arrow is pointed at the mobile sampler.

4. The test on 29 January 1975 was conducted during F stability (winds less than 3 mph). The spray dryer plume slowly climbed and bent in the wind direction. The FLIR unit located at grid position 2.9/3.7 observed an SF_6 burst for several minutes. It appeared to remain compact and airborne for the duration of the FLIR tracking (Figure 13) sequence. The FLIR units were used on several occasions during this test to estimate the ground plume location and provided the same approximate independent results each time. The mobile sampler, because of hazardous terrain, was unable to arrive at the FLIR predicted location. However, even when it was within a few hundred ft of the location it detected no sulfur, indicating that little or no plume was dispersed to the ground. This agreed with the FLIR imagery. Figure 14 shows the SF_6 leaving the stack from the FLIR at 3.7/1.4. Figures 15 through 18 show unique plume formations as seen from 3.7/1.4 during F stability when the wind speed was nearly zero.

5. Figure 19 shows imagery from 23 January 1975. This was typical of the tests during D and E stability. With the SF_6 bursts, the predicted position of FLIR was along the ridge line at position 3.7/2.3.

Figure 10. FLIR Imagery from 2.9/3.7 of Plume
in Aerodynamic Downwash

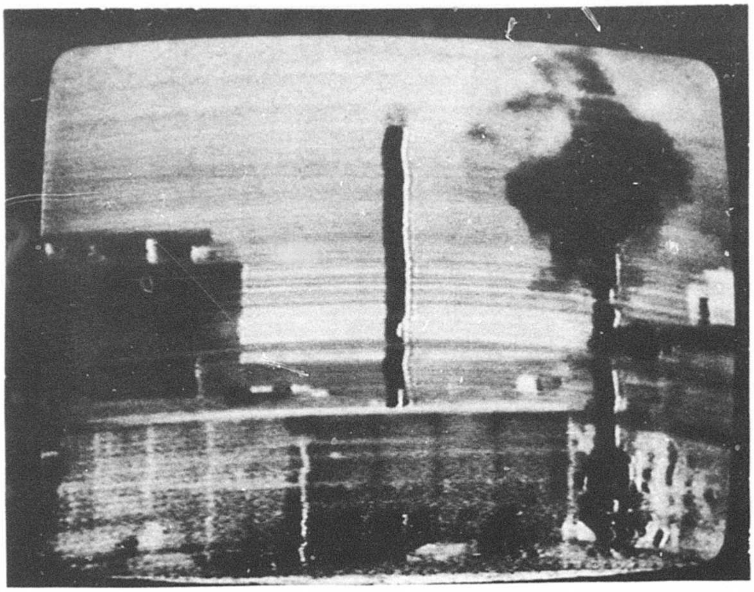


Figure 11. FLIR Imagery from 3.7/1.4 of Plume in Aerodynamic Downwash (Narrow FOV)

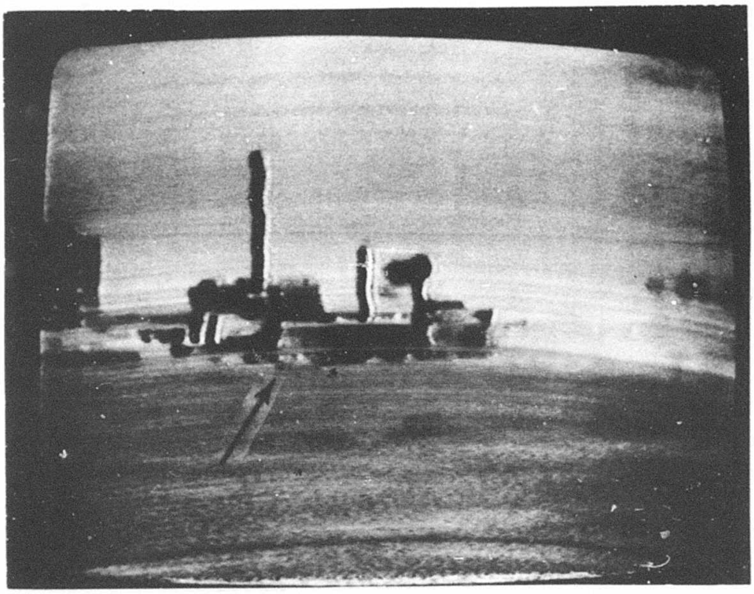
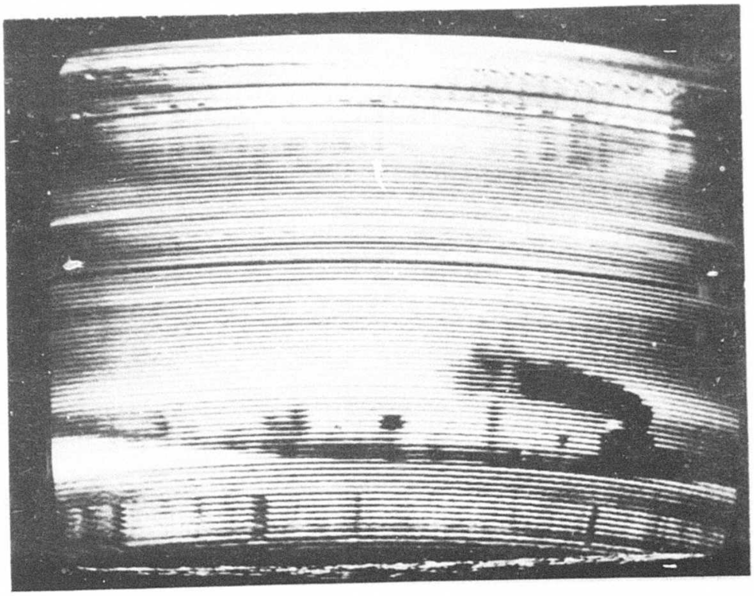


Figure 12. FLIR Imagery from 3.7/1.4 of Plume in Aerodynamic Downwash (Wide FOV)

a.



b.

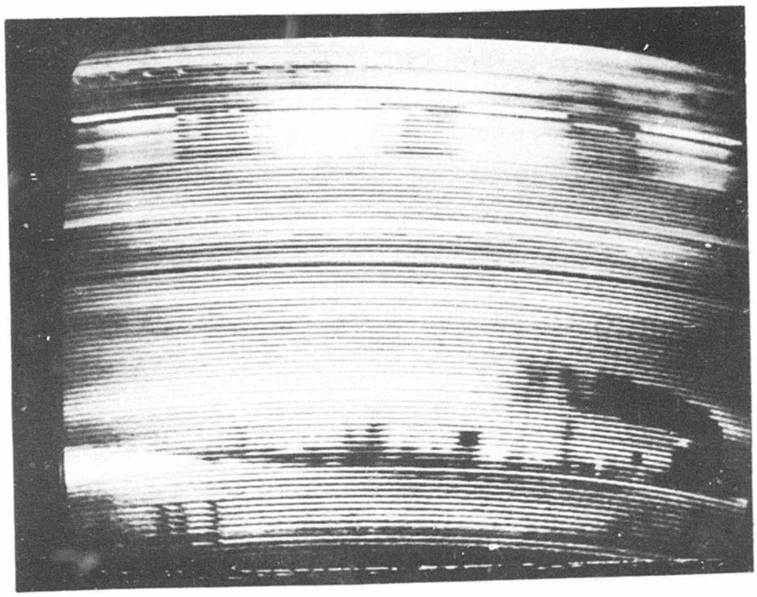
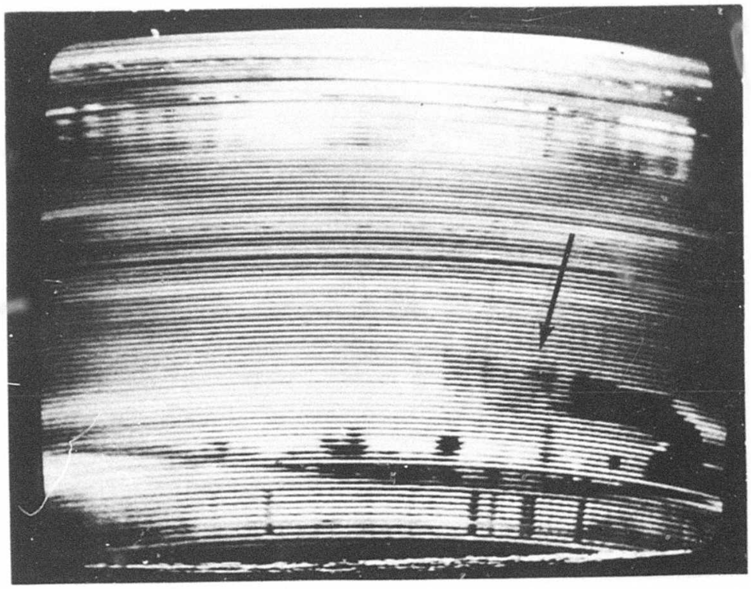


Figure 13. FLIR Imagery from 2.9/3.7 of Plume in F Stability Conditions

c.



d.

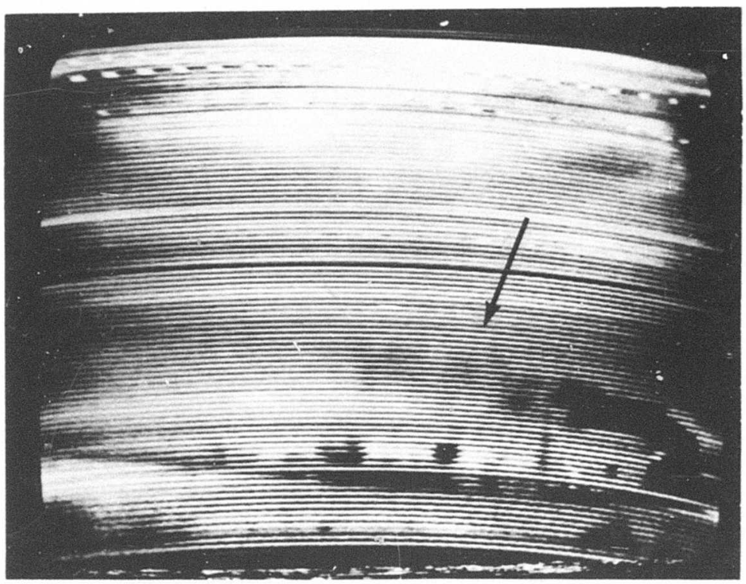
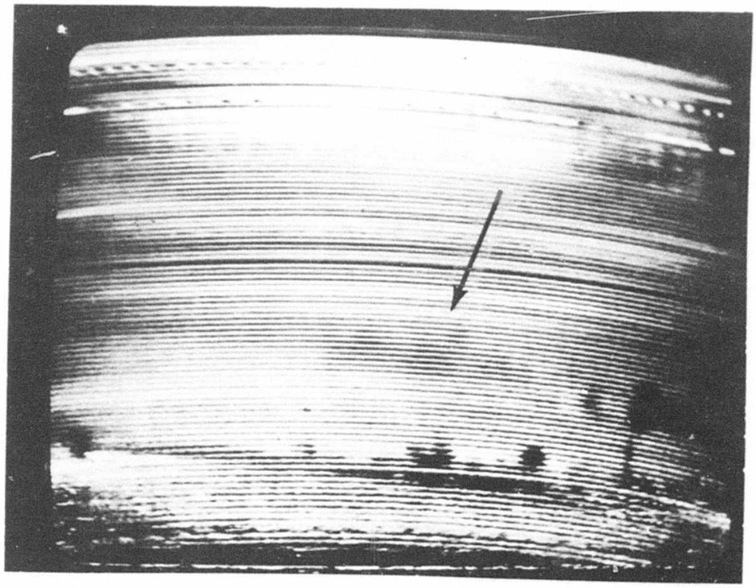


Figure 13. FLIR Imagery from 2.9/3.7 of Plume in F Stability Conditions (Continued)

e.



f.

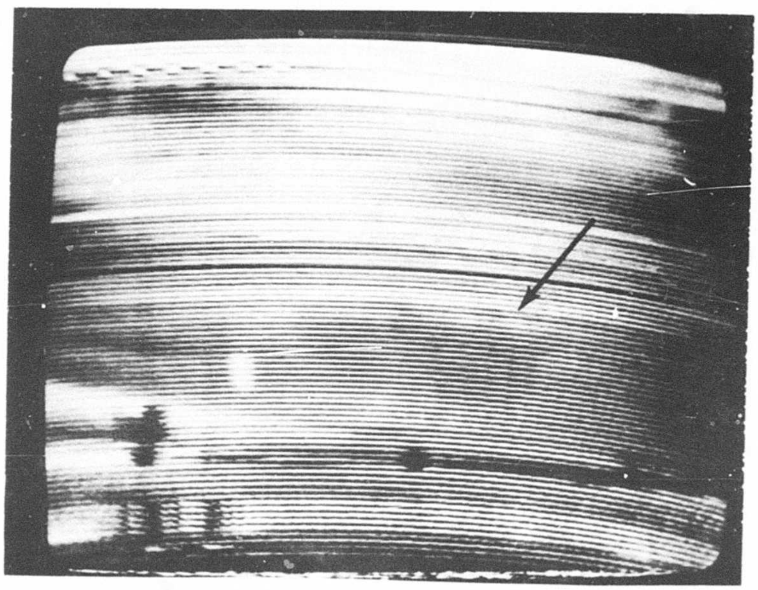
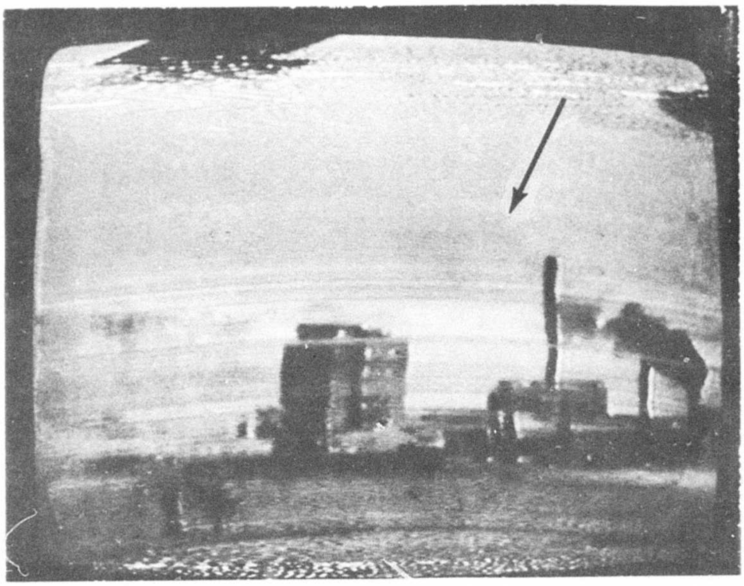


Figure 13. FLIR Imagery from 2.9/3.7 of Plume in F Stability Conditions (Continued)

a.



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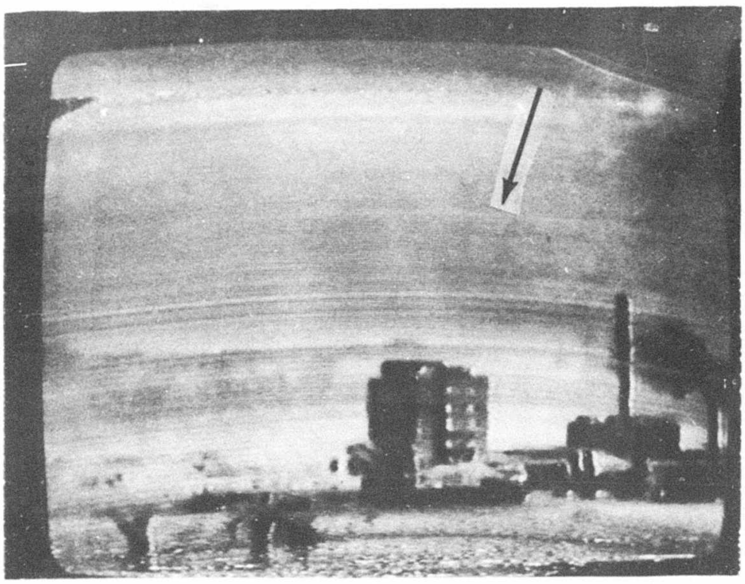


Figure 14. FLIR Imagery from 3.7/1.4 of Plume in F Stability Conditions

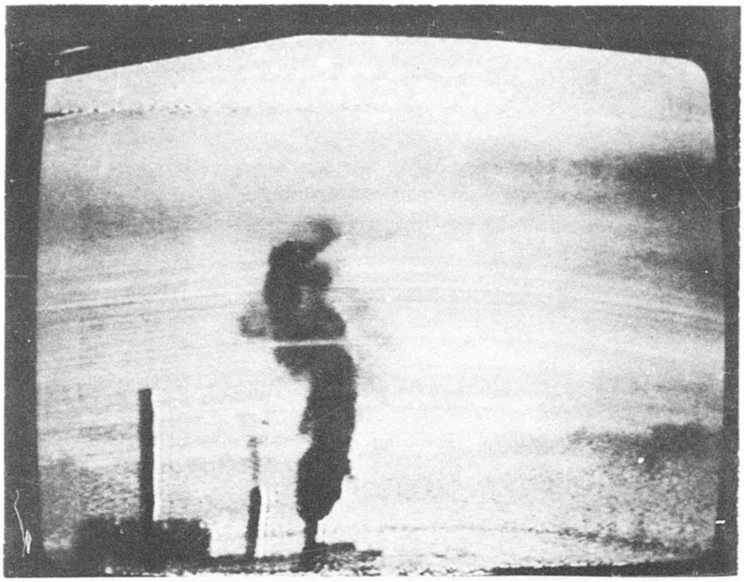


Figure 15. FLIR Imagery from 3.7/1.4 of the Plume Without SF_6 Added During Evening of F Stability Conditions

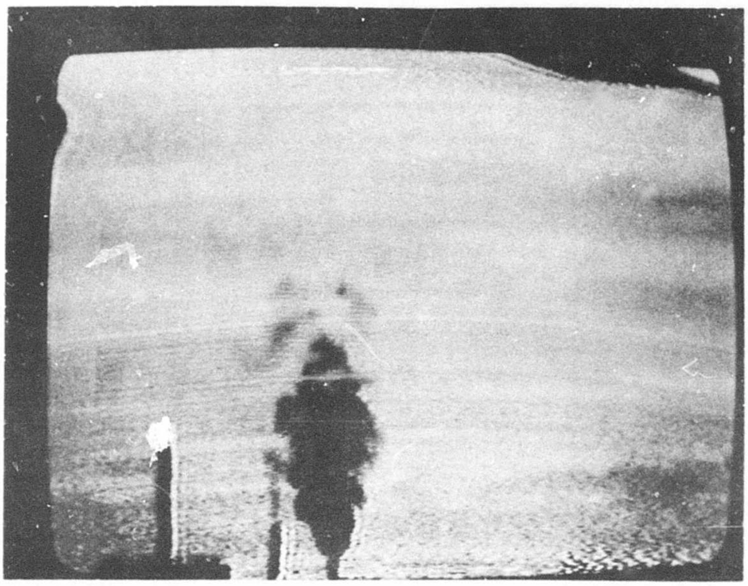


Figure 16. FLIR Imagery from 3.7/1.4 of the Plume Without SF_6 Added During Evening of F Stability Conditions

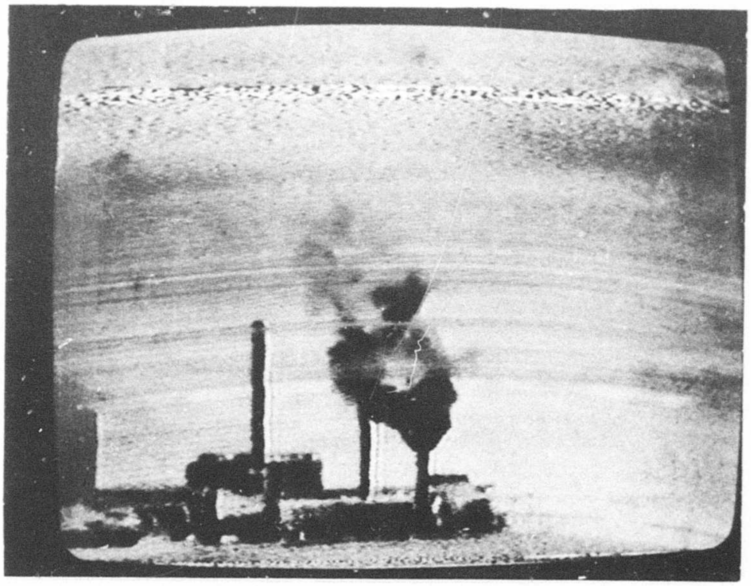


Figure 17. FLIR Imagery from 3.7/1.4 of the Plume Without SF_6 Added During Evening of F Stability Conditions

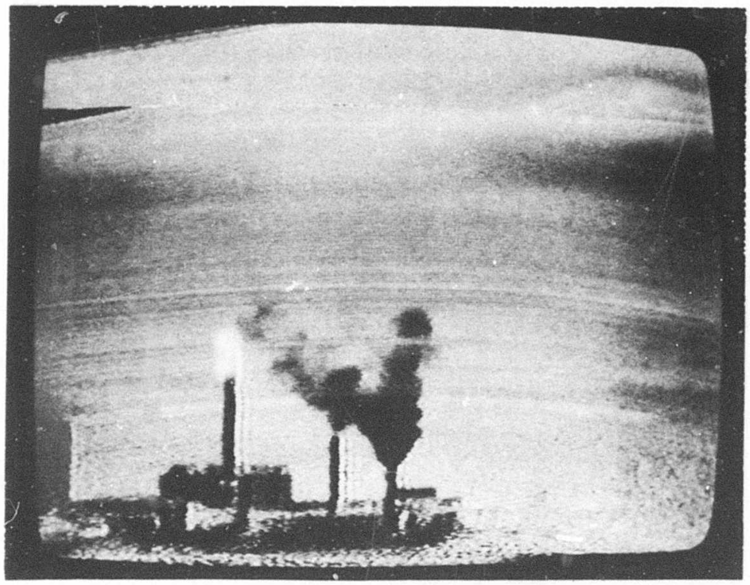
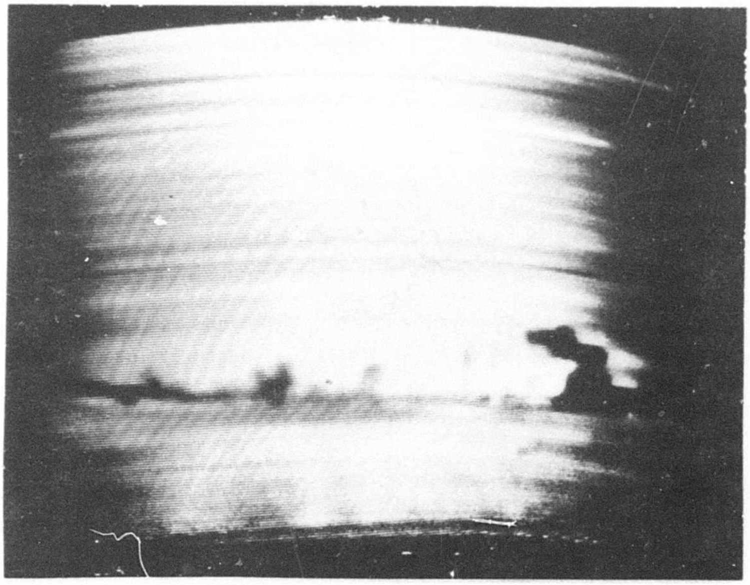


Figure 18. FLIR Imagery from 3.7/1.4 of the Plume Without SF_6 Added During Evening of F Stability Conditions

a.



b.

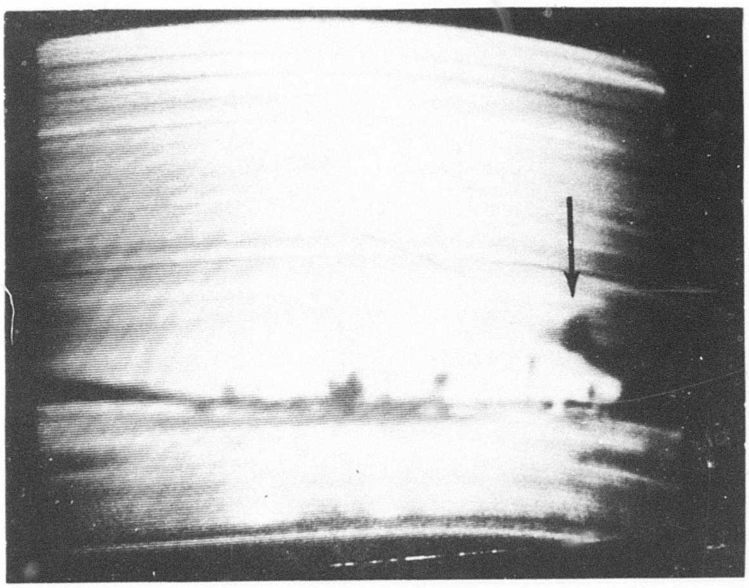
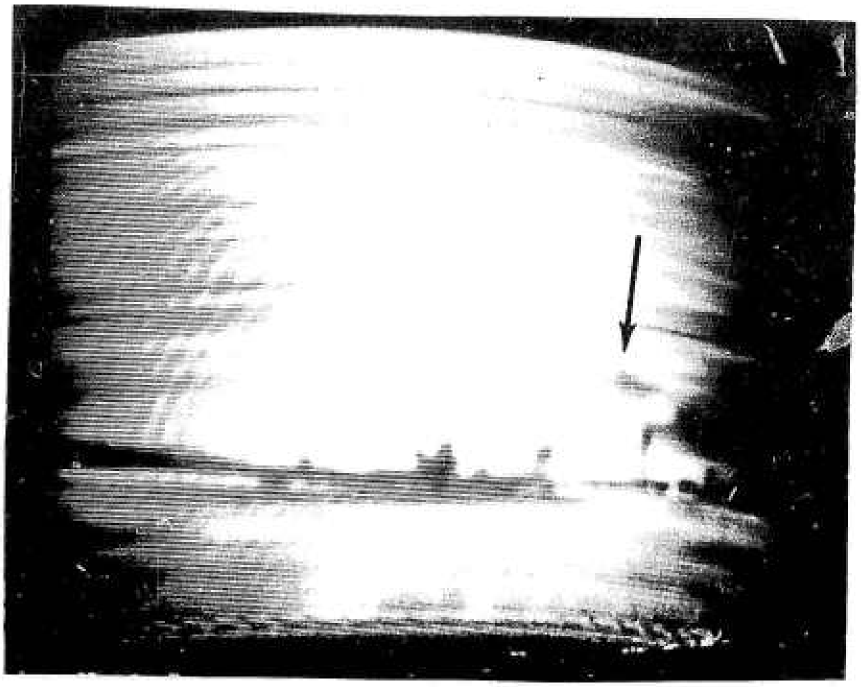


Figure 19. FLIR Imagery from 2.9/3.7 of Plume on 23 January 1975

c.



d.

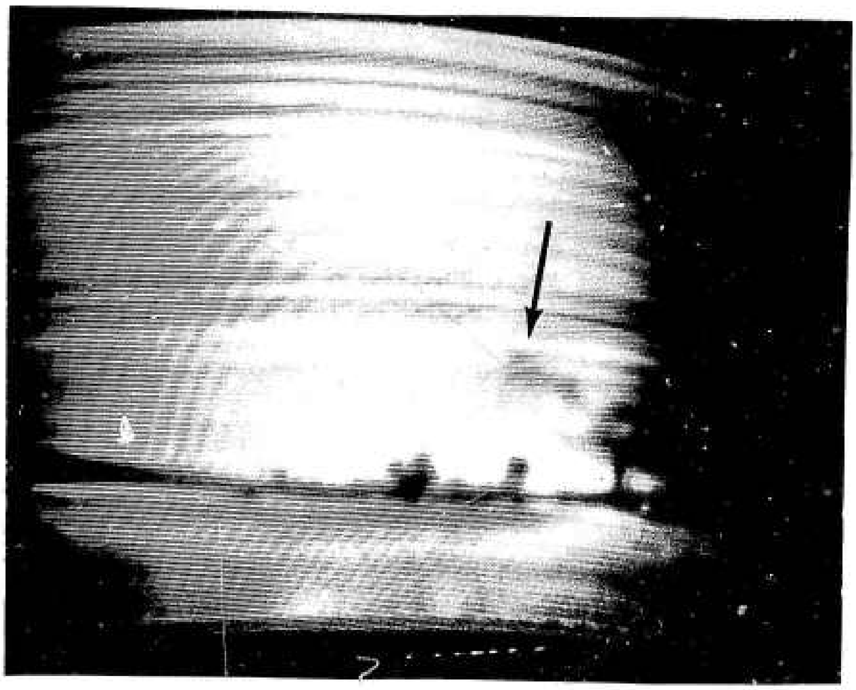


Figure 19. FLIR Imagery from 2.9/3.7 of Plume on 23 January 1975 (Continued)

The test on 23 January 1975 demonstrated the effect of the shifting wind. The mobile sampler detected the plume at position 3.9/2.8 which was confirmed by FLIR. However, when the sampling commenced, the wind shifted so that the ground plume was several hundred yards from the sampling position.

6. Near the end of the test on 23 January 1975, resulted in a unique plume composed of sawtooth-shaped puffs due to the atmospheric instability. Figures 19 and 20 show imagery from 23 January 1975. This was typical of the tests during D and E stability. Figure 19 shows the beginning of the SF_6 burst from grid point 2.9/3.7. The leading edge of the plume reached a mean altitude of about 100 ft with the main body remaining at a 50-75 ft height above ground. Figure 20 is FLIR imagery from 3.7/1.4 of the same event. Figure 20 shows the SF_6 shortly after release, and the dispersal of the SF_6 burst as indicated by the inserted arrows.

7. One interesting sidelight of the main testing was the night monitoring of wildlife at RMA. Figure 21 shows a creature howling into the darkness and tending to its young.

a.

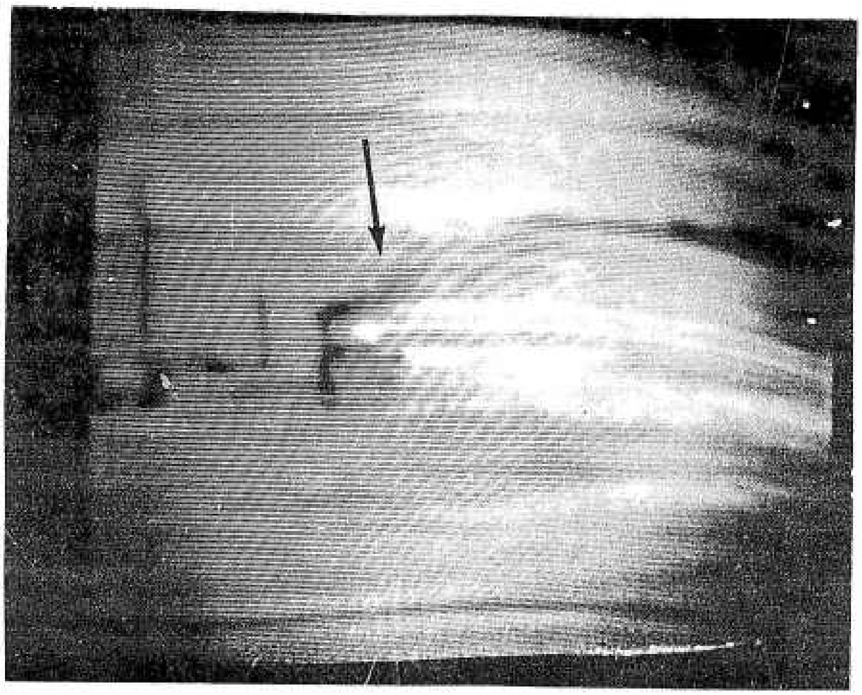
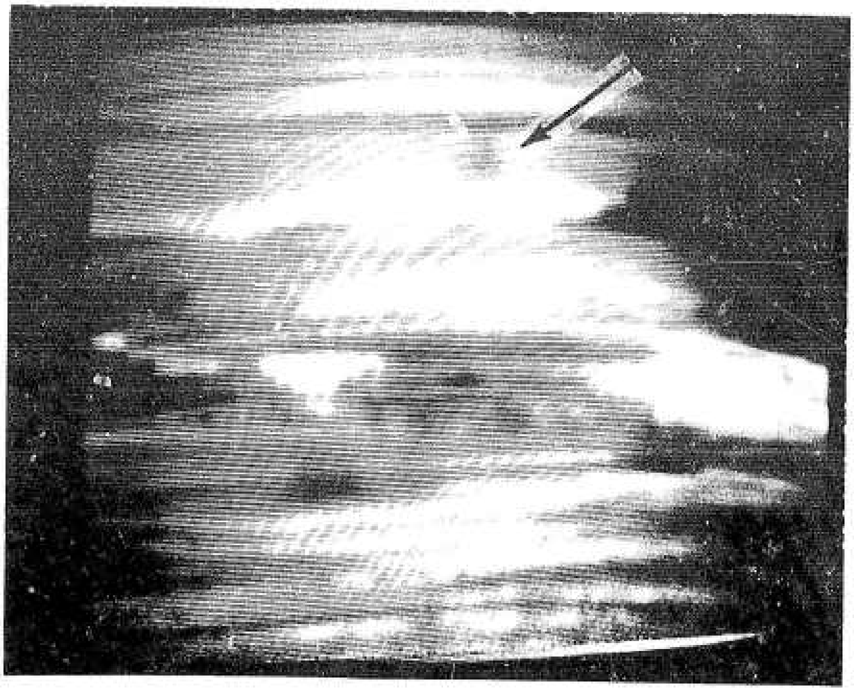


Figure 20. FLIR Imagery from 3.7/1.4 of Plume on 23 January 1975

b.



c.

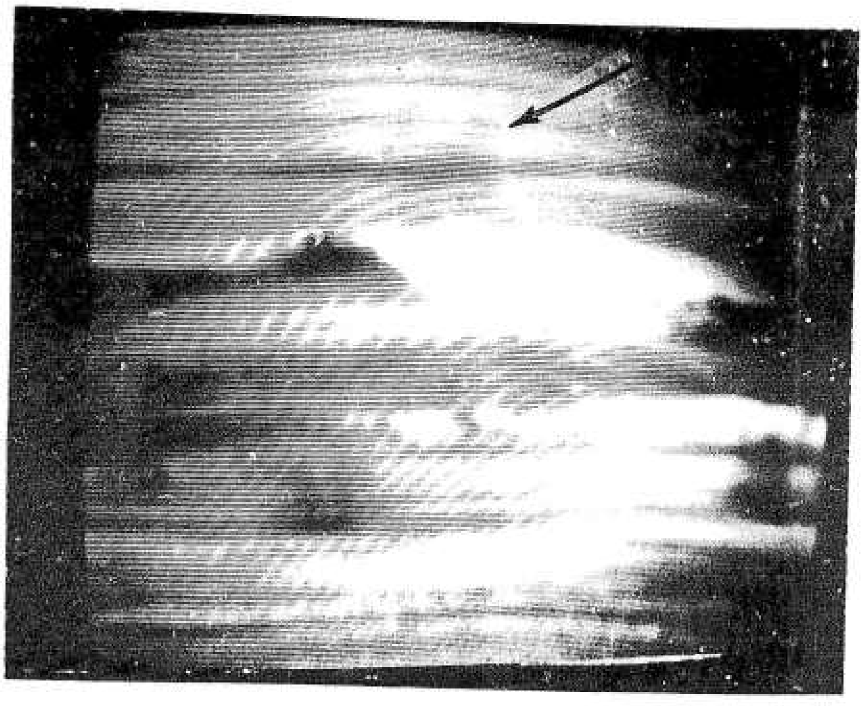


Figure 20. FLIR Imagery from 3.7/1.4 of Plume on 23 January 1975 (Continued)

a.

b.

Figure 21. FLIR Imagery of Wildlife at RMA

CONCLUSIONS

1. FLIR was a valuable tool in assisting the mobile sampler to find the ground position of the plume.

2. The terrain at RMA was conducive to FLIR assistance, as a fast-rising plume usually had its maximum ground concentration at a ridge line when the winds were from the east or west.

3. For flat terrain, FLIR can determine the plume direction and provide a rough estimate of the maximum ground concentration for high plumes. When the maximum ground concentration is expected within ~1000 yd of the stack, FLIR triangulation is accurate to within ~100 ft.

4. FLIR detected SF_6 at a CL value of 2 against a low angle sky background. This is the most sensitive value of an imaging sensor yet reported.

5. The utility of a high spatial resolution thermal imaging device in tracking stack effluent plumes. This method cannot, however, identify particular constituents of the plume at present. A thermal imaging device, coupled with a high spectral resolution spectrometer (such as an interferometer), would give conclusive proof of air pollution offenders in day or night operations, with the video output from the imagery device recorded on tape.

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20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

Experimental results of using a forward looking infrared (FLIR) thermal imaging system to monitor the spray dryer stack effluent at Rocky Mountain Arsenal, Colorado, are presented. The effluent was emitted in the demilitarization process of GB nerve gas.

Since the effluent was mostly water vapor with very small quantities of residue GB, a strong infrared absorber that approximated the molecular

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weight of GB, sulfur hexafluoride (SF_6), was added to the stack to aid tracking. Without the SF_6, the plume extent was seen as readily by visual means as with a FLIR. With SF_6 added to the stack, the plume was tracked from ranges of hundreds of yards to several miles, depending upon the meteorological and background conditions. Finally, two FLIR units, in conjunction with a mobile air sampler unit of the Army Environmental Hygiene Agency, used triangulation to successfully locate the area where the spray dryer plume reached ground level under several meteorological conditions.

Furthermore, it was concluded that a thermal imaging device, coupled with a high spectral resolution spectrometer, would be useful in detecting air pollution during day or night operations.